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Carbon capture and reuse in an industrial district:

a technical and economic feasibility study

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Abstract: In recent years, increasing attention from both industries and research has been focused on carbon capture and, subsequently, storage technologies. These technologies will contribute to companies' strategies for reducing greenhouse gas emissions from fossils fuels. However, less effort has been spent on evaluating another interesting option after carbon capture: carbon utilisation or reuse. A feasibility study regarding an Italian industrial district is discussed: the district is characterised by the nearby locations of a CO2 producer (i.e. an natural gas combined cycle power plant) and a CO2 user (i.e. a sugar factory). The annual average CO2 emission by the power plant is about 1.7 million tonnes. Under current conditions the sugar factory 'produces' CO2 to use it in the sugar refining process; thus, the idea is to evaluate the feasibility of capturing CO2 emitted from the power plant and reusing it in the sugar factory process from both a technological and an economic point of view. The results indicated a cost saving of about 42% in the operational costs of the sugar factory due to the introduction of the carbon reuse technology.

Keywords: carbon capture, carbon reuse, industrial symbiosis, feasibility study.

1. Introduction

Carbon capture and storage (CCS) technologies are developing rapidly worldwide from pilot to full scale projects, mainly due to their potential contribution to mitigation of carbon dioxide (CO2) emissions (Lombardi, 2003; UNEP, 2005; Lindner et al., 2010; Pires et al., 2011; García-Gusano et al., 2013; Man et al., 2014). CO2 is captured at fixed point sources, such as power plants and cement manufacturing facilities, and transported to specific destinations for storage. Different technological options for carbon capture have been available for several years, for example absorption, adsorption, separation by membranes, and cryogenic separation (Herzog, 1997; Yu et al., 2012). Current options for CO2 storage mainly include geological storage, ocean storage, and mineralisation. However, the debate about the overall economic and environmental effectiveness of CCS systems is still open and controversial (Chaudhry et al., 2013): the critical point in CCS is the storage option (Camara et al., 2013), rather than the carbon capture technology developments, which have been consolidated.

On the other hand, less attention has been focused on two other options: CO2 utilisation and reuse. CO2 utilisation refers to the possibility of using CO2 for other end uses, such as in building-material production, fuels, and chemicals (Aresta et al., 2013).

There is no single, universally applicable pathway for CO2 utilisation. In brief, CO2 can be utilised in three major pathways:

1) as a storage medium for renewable energy (DNV, 2011);
2) as a feedstock for various chemicals (Aresta et al., 2013);
3) as a solvent or working fluid in several processes (e.g. in the food industry).

CO2 reuse refers to use of the major greenhouse gas captured from industrial plants rather than releasing it (and its warming potential) into the environment (Laumb et al., 2013; Li et al., 2013).

The focus of the proposed study is on CO2 reuse in an industrial district: the basic idea is to apply the concept of industrial symbiosis (Gnoni et al., 2011; Sokka et al., 2011; De Felice et al., 2014) to increase the environmental sustainability of both the whole industrial district and the single companies by reusing CO2 captured from one plant in another plant where it is required during processes. This strategy, compared to traditional CCS, could be more effective from an economic point of view, as it aims to maximise CO2 reuse as an industrial resource to make a profit by exploiting it as a primary resource (DNV, 2011; Laumb et al., 2013). It still has to be captured and extracted from industrial emissions, but, instead of being stored, it will be reused in new chemical, industrial, or biological applications. It has to be noted that CO2 reuse does not fully replace storage as, depending on the application, it could eventually return to the atmosphere after it has been used. However, from a global perspective, it will contribute to reducing carbon emission levels (Ng et al., 2013). The CO2 reuse also contributes to the generation of economic value, opening up possibilities to develop new technologies, markets, and employment. Moreover, CO2 reuse could be economically convenient if the additional energy expended to capture the CO2 is not high (Harkin et al., 2010); thus, an industrial symbiosis strategy based on reusing CO2 locally – that is, where it is emitted – could be a very effective solution (Sokka et al., 2011). The current paper proposes a technological and economic analysis for evaluating the capture of CO2 and its reuse in an Italian industrial district; a general framework for supporting CO2 capture and the reuse process is also outlined. Furthermore, the results obtained demonstrate the potential of reusing CO2 in industrial districts to support new business models and services.

The remainder of the paper is organised as follows: the main features characterising the industrial district under analysis are described in Section 2; next, in Sections 3 and 4, the technological and economic analyses are respectively discussed.

2. The industrial district: main features

The industrial district under analysis is composed of several industrial firms, and the focus of this study is on two major plants: a natural gas combined cycle (NGCC) power plant and a sugar factory. The NGCC power plant has a total capacity of 770 MW, allowing an annual electricity production of about 4 billion kWh, and an annual steam production of about 20,000 tonnes for industrial use. Focusing only on carbon emissions, the annual average CO2 emission level is about 1.7 million tonnes, estimated for a productivity level of 8,000 h/year. The sugar factory is located near the power plant; each location is outlined in Figure 1.

The white sugar is mainly produced from sugar beets; the plant’s annual production capacity is about 750,000 tonnes of sugar beet, thus producing about 84,300 tonnes of white sugar.

Figure 1. Location of the two plants under analysis (red: the sugar factory; green: the power plant)

Processes in the sugar factory start after the raw material washing process. Sugar beets are reduced into cossettes by a mechanical shredding process in order to offer a maximum surface area for the next extraction process. Following that, the sugar juice is extracted from the sugar beets: cossettes are lifted from the bottom to the top of the diffuser as hot water washes over them, absorbing the sugar. After the juice extraction, a carbonation process is carried out to remove impurities from the raw juice; the output is the so-called thin juice. The carbonation process requires lime milk and CO2; during the process CO2 reacts with lime, thus producing calcium carbonate (limestone). Lime milk and CO2 are produced in vertical and rotary kilns fired by natural gas, where the limestone dissociation is obtained by combustion at high temperature.

Next, a refining process is carried out to transform the thin juice into thick juice; the product is now characterised by a high (i.e. about 70%) sugar concentration. In order to produce sugar in a crystalline form, water evaporation is required: the crystallisation process is developed at a reduced temperature and pressure in vacuum pans. The output is defined as ‘massecuite’, which is a mix of sugar crystals and juice. Finally, clarification and filtration produce white sugar. The process is summarised in Figure 2.

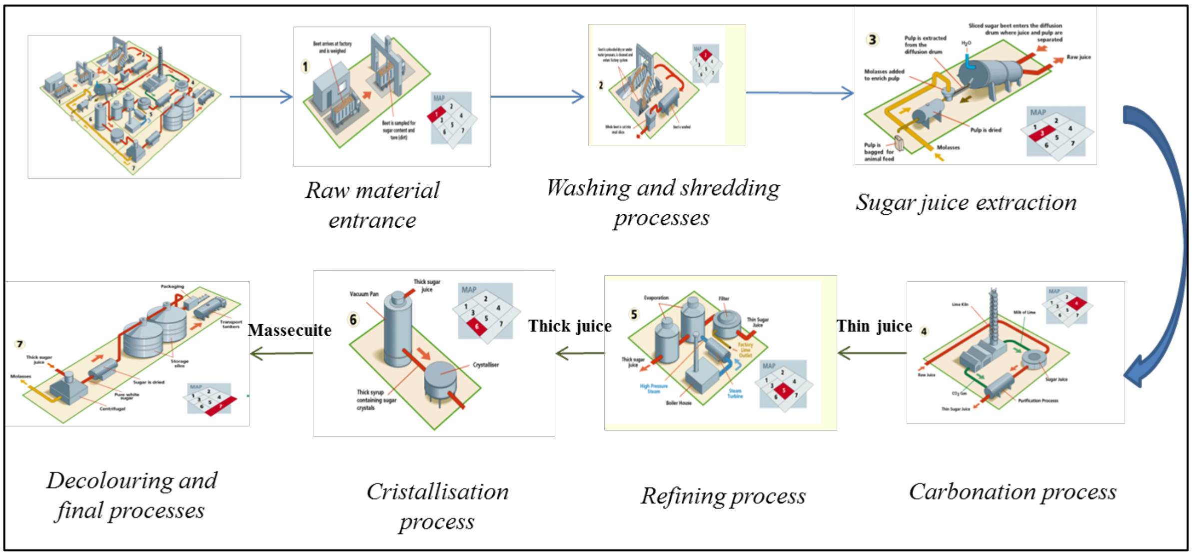

Figure 2. The analysed sugar production process

The process in which carbon reuse is evaluated is the carbonation process, in which CO2 is a process input. The idea is to capture CO2 emitted from the power plant for reuse in the carbonation process in the sugar factory, as depicted in Figure 3.

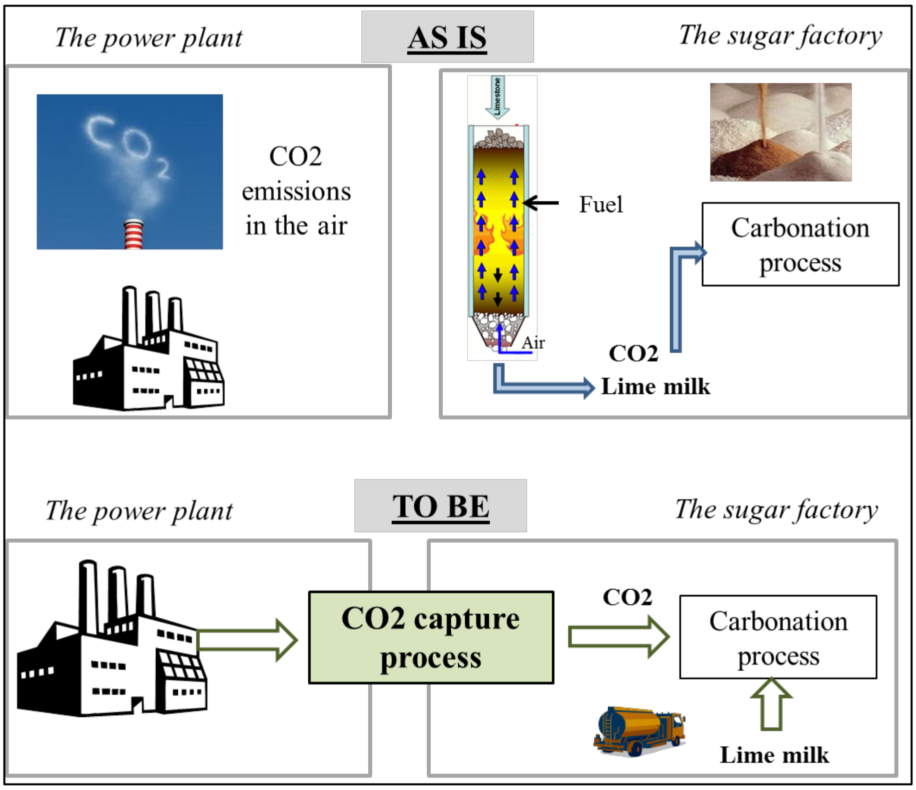

Figure 3. The CO2 capture and reuse model proposed for the industrial district

Thus, the vertical kiln for producing CO2 and lime milk will be definitively eliminated from the sugar refining process as the lime milk will be purchased directly from an external supplier. Furthermore, a carbon capture process has to be added in the industrial district with the aim of capturing emission from the NGCC power plant and transporting it to the sugar factory. Furthermore, the insertion of a carbon capture process will lead to determine a negative impact on the power generation efficiency; these values are strictly connected to the technology applied for capturing CO2. Thus, a feasibility study based on evaluating technology options for capturing CO2 is proposed in the next section; an economic analysis is also discussed with the aim of supporting both firms in evaluating the proposed solution.

3. The technological analysis

The technological assessment was carried out in different phases. The first analysis concerns the phase in which the capture technology is applied (before or after the combustion process). CO2 capture could be developed in fossil fuel power plants following two alternative routes (IPPC, 2011; Favre, 2011): before and after the combustion process. The first type refers to removing CO2 from fossil fuels before combustion is completed. Two main methods are currently applied (Global CCS Institute, 2012a,b): pre-combustion by a decarbonisation process and denitrogenation by an oxy-combustion process (often called oxy-combustion).

The first one is called a *pre-combustion capture process*: the fossil fuel and steam are converted into synthesis gas (or syngas) in a traditional steam reformer; the most common configuration involves gasification with air or oxygen. Syngas contains carbon monoxide (CO) and hydrogen gas; subsequently, the CO reacts with steam to form CO2. Typical applications of the pre-combustion capture process are in integrated gasification combined cycle plants (Falcone et al., 2007; Damen et al., 2011; Mantripragada & Rubin, 2013; Franz & Maas, 2014). The *oxy-combustion capture process* significantly modifies how the combustion process is conducted: it uses oxygen instead of air, thus eliminating nitrogen from the oxidant gas stream and producing a CO2-enriched flue gas. This flue gas is ready for sequestration after water has been condensed and other impurities have been separated out. Its main limitation is due to the stringent requirement for nearly pure oxygen – rather than air – for the fuel combustion: this requirement provides positive impacts, as the final product is nearly pure CO2, but also negative ones, due to the high capital cost of producing oxygen (Li et al., 2011).

Briefly, these technologies – based on either carbon or nitrogen removal – aim to remove CO2 from the process before combustion; thus, they could generate a high-CO2-concentration waste gas stream. The basic idea is that if CO2 concentration or pressure or both increase, capture could become easier.

The *post-combustion capture process,* or PCC, uses chemical or physical processes to capture CO2 after the combustion process; this alternative is characterised by a reduced impact on operations of the power plant itself, even if the overall plant complexity increases. Thus, pre-combustion capture technologies become competitive especially for new fossil fuel power plants, as the capture process requires strong integration with the combustion process.

The three options were compared based on different factors. The first parameter analysed was the easy adaptability of these technologies in an existing power plant. With regard to this issue, PCC was evaluated as the most effective strategy as it can be more easily retrofitted to the existing power plant (Tuinier et al., 2011). Next, the influence of inlet flow conditions on each of the alternatives was evaluated, and data regarding the required conditions expressed in terms of pressure, temperature, and target mixture are reported in Table 1. By comparing these values with those characterising the current outflow of the power plant under analysis, PCC was confirmed as the most effective solution.

Carbon capture strategy	**Target mixture**	**Required operating conditions (expressed in terms of pressure (P) and temperature (T)**
Oxy-combustion	O2/N2	P: Atmospheric; T: ambient
Pre-combustion	CO2/H2	P: up to 80 bar; T: 300–700 ◦C
Post-combustion	CO2/N2	P: atmospheric; T: 100–250 ◦C
Source: Favre, 2011		

Table 1. Inlet flow characterisation for each alternative

Finally, in Table 2, the costs estimated according to the type of power plant (i.e. PC, IGCC, and NGCC) and type of fuel used in the power plant are reported for each CO2 capture process previously analysed.

	FUEL TYPE			
	Coal			***NG***
CAPTURE ROUTE	Post-combustion	Pre-combustion	Oxy-combustion	Post-combustion
Reference plant without capture	*PC*	*IGCC*	*PC*	*NGCC*
Net efficiency with capture (LHV,%)	30.9	33.1	31.9	48.4
Net efficiency penalty (LHV, percentage points)	10.5	7.5	9.6	8.3
Relative net efficiency penalty	25%	20%	23%	15%
Overnight cost with capture (USD/kW)	3808	3714	3959	1715
Overnight cost increase (USD/kW)	1647	1128	1696	754
Relative overnight cost increase	75%	44%	74%	82%
LCOE with capture (USD/kW)	107	104	102	102
LCOE increase (USD/kW)	41	29	40	25
Relative LCOE increase	63%	39%	64%	33%
Cost of CO2 avoided (USD/tCO2)	58	43	52	80

Table 2. Estimated costs defined according to each capture option, type of fuel, and type of power plant (source (FInkenrath, 2011)

The next step was to evaluate the *specific technology process that would be adopted for the PCC*: by analysing technologies based on the main physical processes driving the carbon separation, different options could be outlined; however, technologies are heavily influenced by the type of industry, its location, and other context constraints (Di Bona et al., 2014). The current technologies for PCC are absorption, adsorption, the cryogenic process, and gas separation through a membrane. Technological scouting was carried out to highlight the most effective option for the specific case study. The main features are analysed as follows:

- **Absorption** (based on chemical or physical processes): This is based on the physical absorption of CO2 into a solvent; next, a weakly bonded intermediate compound is produced, which could be regenerated with the application of heat producing the original solvent and a CO2 stream. Regeneration could also be achieved by using pressure reduction alone or in conjunction with heat. The most frequently used solvent type is amine-based chemical absorbent (Rao & Rubin, 2002; Wang et al., 2011). Chemical absorption could be characterised by scale problems, efficiency, and stability as chemical solvents are used for high-volume gas flows with a relatively smaller fraction of valuable products. In physical absorption, the CO2 molecules are dissolved in a liquid solvent, and no chemical reaction takes place.
- **Adsorption**: In physical adsorption, gas is adsorbed on a solid surface; the most frequently used adsorbents include activated carbon, alumina, metallic oxides, and zeolites (Li et al., 2011; Wang et al., 2011). Furthermore, chemical adsorption is also an alternative option that is less often applied (Chaffee et al., 2007; Li et al., 2013).
- **Low-temperature distillation**: The cryogenic process of separation is applied to split CO2 from the flue gas stream by condensation. This method is efficient if the CO2 concentration is high (more than 90%); furthermore, higher energy consumption is required for gas compression and cooling. On the

other hand, the CO2 is produced in a liquid state, allowing an easier transportation process. The great advantages of the cryogenic CO2 capture process compared to previously analysed technologies are that no chemical absorbents are required and the process can be carried out at atmospheric pressure (Brunetti et al., 2010; Tuinier et al., 2011).

- **Gas separation membranes**: Membranes act as contacting devices between the gas stream and the liquid solvent; the device may or may not provide additional selectivity (Habib et al., 2011). These offer some advantages over the conventional contacting devices (e.g. packed columns) as they are more compact and are not susceptible to flooding, entrainment, channelling, or foaming. They require stable operating conditions because an equal pressure level on both the liquid and gas sides is essential for enabling CO2 transport across the membrane.

Finally, other pilot technologies are based on a mineralisation (and bio-mineralisation) process; they use the carbon mineralisation process, that is, the process of converting CO2 into stable minerals (mineralisation). The use of carbon mineralisation as a CO2 capture method is limited by two critical factors: the slow speeds at which these minerals can be dissolved and CO2 can be hydrated, and the high energy needed to hasten the overall process.

A comparative analysis was carried out based on operational factors which contribute to the overall efficiency characterising each technology. The main factors analysed derive from Brunetti et al. (2010) and are detailed as follows:

- **Operational flexibility**: as membrane devices for gas separation usually operate under continuous steady-state conditions, operational flexibility refers to the capability of the specific device to guarantee high efficiency rates under variable flue gas flows for either a short or a long period.
- **Turndown**: the capability to work with high efficiency at reduced demand.
- **Reliability**: the technology’s capability to provide continuous operations without unplanned shutdowns.
- **Modularity**: affects how easy the scaling up process required by future expansions would be.
- **Energy intensity required by the overall capture process**: refers to the overall energy requirements which also contribute to reducing the efficiency of power cycles.

Furthermore, based on other recent studies (Powell & Qiao, 2006), two more factors were evaluated in the proposed analysis:

- **Adaptability**: the speed required for adapting the device to inflow variations.
- **Roll out speed**: the total length of the process time required by the device.

Values of each operational factor estimated for the four PCC technologies are listed in Table 3.

Operational factor	**Technology process**			
	Absorption	***Adsorption***	***Gas separation membranes***	***Cryogenic process***
Operational flexibility	Medium	High	High (for CO2 > 20%)	Low

			Low (for CO2 < 20%)	
Turndown	Down to 30%	Down to 30%	–	–
Reliability	Medium	Medium	Very high	Low
Modularity	Medium	Medium	Very high	Very low
Energy intensity	Low	Medium	High variable *	High
Adaptability	Quick (within 5–15 min)	Quick (within 5–15 min)	Instantaneous	Slow
Rollout speed	1 hour	1 hour	Rapid (less than 10 min)	8–24 hours
** It could vary from 0.5 to 10 MJ per kg of CO2 produced*				

Table 3. Comparison between PCC technologies based on operational factors proposed by Brunetti et al. (2010) and Powell & Qiao (2006)

Furthermore, the analysis was integrated by evaluating the global technical efficiency of each technology. Based on the analysis proposed by Brunetti et al. (2009), three indicators were introduced in the feasibility study, namely:

- Quantity of CO2 contained in the inlet gas: This factor represents the required conditions of each capturing technology as the ‘pollution’ level of the inlet gas could strongly affect the technological performance.
- Quantity of CO2 contained in the outlet flow: This factor defines the final composition of the captured CO2 flow; it affects the final destination of CO2 flows (i.e. reuse for industrial applications and/or storage).
- Total quantity of CO2 captured: This defines outlines the process yield characterising each technology.

Quantitative values are shown in Table 4. After analysing each operational and technical factor, the evaluated technological process for capturing CO2 chosen was the **membrane technology** as it could guarantee the most efficient solution under the current operating conditions.

Technical factor	**Technology process**			
	Absorption	***Adsorption***	***Gas separation membranes***	***Cryogenic process***
CO2 presence in the inflow gas [molar %]	>5	>10	>15	>5
CO2 purity in the outflow [%]	>95	75–90	80–95	99.99
CO2 recovered [%]	80–95	80–95	60– 80	99.99

Table 4. Comparison between PCC technologies based on technical factors

Next, the problem was to evaluate the most efficient type of membrane for the analysed application; three main types are currently applied for carbon capture processes: ceramic, polymeric, or mixed matrix based. Briefly, permeability and selectivity are the two main parameters that characterise the performance of a membrane material; they are directly connected from an application point of view to productivity and purity, respectively (Bernardo & Clarizia, 2013). On the other hand, other technical parameters are also relevant for evaluating the overall efficiency of each membrane type; a synthesis has been deducted from Drioli et al. (2010) and is presented in Table 5.

Factor	**Membrane type**		
	Ceramic	***Polymeric***	***Mixed matrix***
Purchase cost	High	Low	Moderate
Operating temperature range	Large	Limited	Moderate
Thermal stability	High	Moderate	High
Chemical stability	High	Moderate	High
Solvent stability	High	Limited	Limited
Resistance to harsh conditions	High	Limited	Limited
Mechanical strength	Poor	Good	Excellent
Packing density	Poor	High	High
Resistance to handling	Brittle	Robust	Robust
Swelling	Free of swelling	Frequent	Free of swelling
Plasticisation	Free of plasticisation	Frequent	Moderately frequent
Reparability	Extremely complex	Easy	Easy

Table 5. Comparison between membrane types

The analysis was focused on polymeric and ceramic membranes. Starting from polymeric membranes, this technology is currently characterised by high technical performance (e.g. in terms of permeability and selectivity values); costs involved are usually lower than with ceramic and mixed matrix types. On evaluating the specific application, it was found that the use of a polymeric membrane is not perfectly effective, mainly due to the following issues:

- The CO2 concentration is usually very low (about 3–4%) in NGCC power plants; thus, the carbon capture technology has to process a high gas inflow, leading to a reduction in its overall efficiency.
- Due to high flue temperatures and the presence of aggressive chemicals, polymeric membranes could wear out quickly. In order to prevent this phenomenon, a cooling process has to be carried out together with a filtration process before the CO2 capture; these additional requirements contribute to an increase of the total investment cost even if the unitary process cost is lower compared to other membrane types.

Thus, the ceramic membrane technology was evaluated as the best option for the CO2 capture in the analysed application. The main factors influencing this evaluation are its capability to operate with high temperature gases and its high chemical resistance (Habib et al., 2011; Franz et al., 2014).

Finally, the overall decision process proposed in the feasibility study has been summarised in Figure 4.

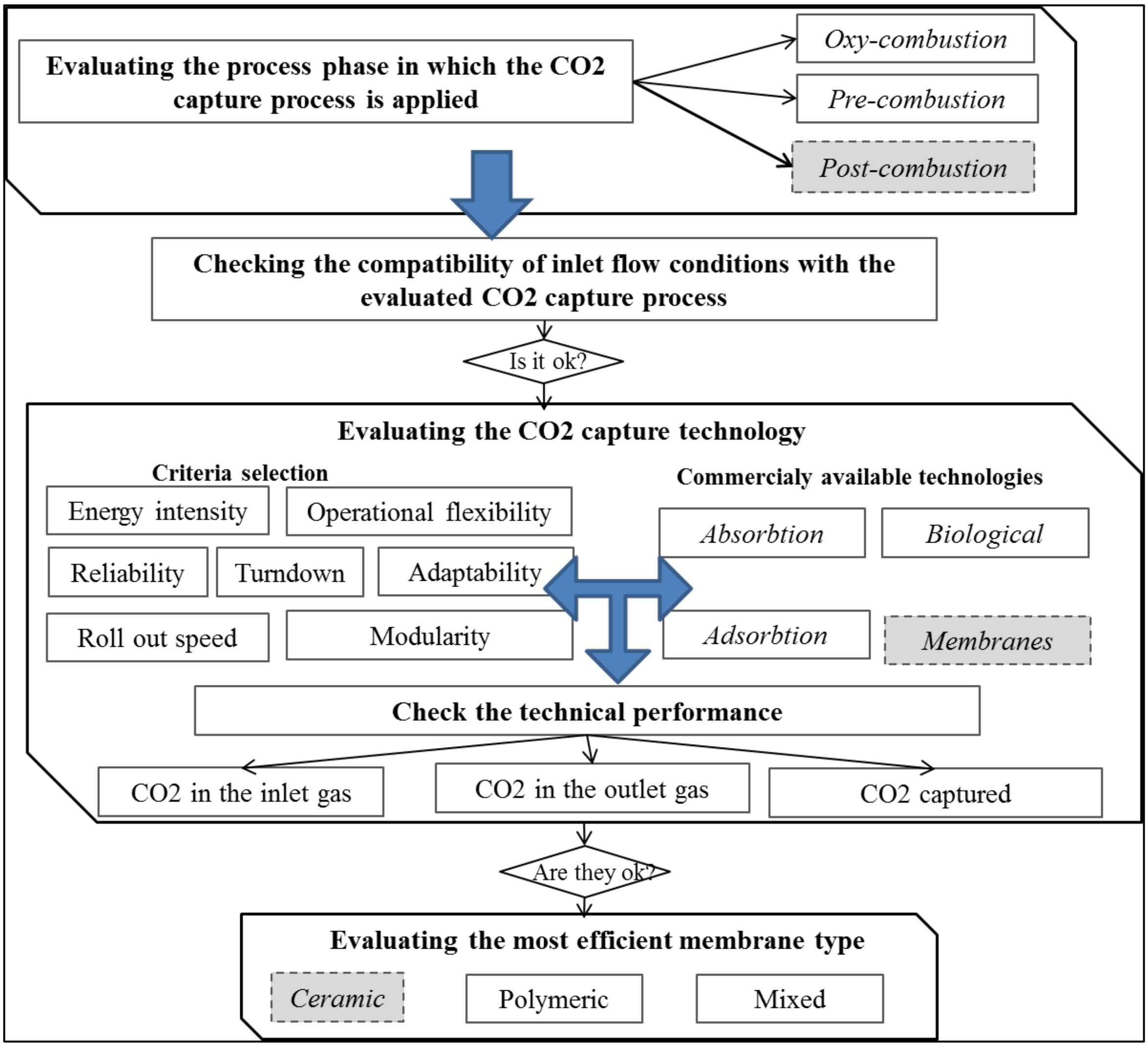

Figure 4. The decision problem for evaluating the carbon capture process option for the feasibility study

4. The economic analysis

Input data for the economic analysis were deduced from historical values characterising the power plant and the sugar factory. All values are reported in Table 5.

The focus of the feasibility study was on evaluating the economic feasibility of adding a carbon capture process for providing inputs required by the carbonation process in the sugar factory. As defined in Section 2, a high-temperature kiln is currently used to produce lime milk and CO2. Two scenarios were compared, as follows:

- The ‘as is’ scenario: CO2 from the power plant is emitted into the atmosphere and the CO2 required for the carbonation process is produced – together with lime milk – internally in the sugar factory by a high-temperature kiln.

  The ‘to be’ scenario: The proposal is to eliminate the kiln for producing CO2 and lime milk as CO2 is obtained by capturing CO2 power plant emissions; lime milk is purchased from an external supplier. In this scenario, one process is eliminated (i.e. the high-temperature kiln) from the sugar factory and one process (i.e. carbon capture) is added downstream to the power plant.

Input data regarding material requirements are essentially the quantity of CO2 and lime milk required for the carbonation process based on its daily production rate (expressed in terms of sugar feed). Data characterising the ‘as is’ scenario data mainly concern the sugar factory: the most important value is the total daily operational cost of managing the high temperature kiln; this value includes the cost of the fuel purchase necessary for the combustion process in the kiln as well as the purchase cost of raw materials (limestone, etc.). The unitary cost of the lime purchase was deduced from a field analysis developed by the sugar factory; it also includes the cost of transportation from the supplier to the factory. The estimated total operational unitary cost (i.e. €23/tonne) was derived from Merkel et al. (2010), who give this average value for CO2 capture processes based on a ceramic membrane. Furthermore, the total estimated cost of CO2 transportation has been deduced from a study by the IEA (IEA GHG, 2002). The distance between the two plants is about 1 km as they are located in the same industrial districts.

Three main cost contributions were evaluated in the ‘to be’ scenario based on the unitary costs: the total cost of capturing CO2, the cost of transporting it from the power plant to the sugar factory, and the total cost of purchasing lime milk from an external supplier. All data are presented in Table 5.

Based on these assumptions, the total daily ‘to be’ cost was estimated as €27,066.51 compared to the current cost of €47,227.86. The introduction of the carbon capture and reuse processes provides a saving of about 58% of the operational costs of the sugar factory.

Positive impacts have been also estimated for the power plant; the main benefit concerns its environmental impact, which could also be translated into economic benefits. Thus, an estimated decrease in CO2 emission of about 7% of the plant’s total emissions could be achieved if the carbon capture technology were applied; otherwise, a negative impact on its operations could be estimated with a slight decrease (within 15%) in its overall efficiency rate due to the introduction of the carbon capture process (UNEP, 2005).

	DESCRIPTION	**VALUE**
Input data	Average inflow of sugar feed [tonnes/day]	6908.08
	Average lime requirement for the carbonation process [tonnes/day]	193.43
	Average CO2 requirement for the carbonation process [tonnes/day]	278.43
‘As is’ data	**Daily operational cost of the high temperature kiln [€/tonne] (A)**	**47,227.86**
	CO2 daily emission level from the power plant [tonnes/day]	*5,100*
‘To be’ data	Unitary cost of lime purchase from an external supplier [€/tonne]	100
	Unitary operational cost of CO2 capture process based on ceramic membrane technology [€/tonne]	23
	Total daily cost of lime milk purchase [€/tonne] (B)	**19,342.62**
	Total daily cost of CO2 capture [€/tonne] (C)	**6,403.89**
	Total daily cost of CO2 transportation [€/tonne] (D)	**1,320.00**
	Total ‘to be’ cost (B + C + D) [€/tonne]	**27,066.51**

	Variation (A – B + C + D) [€/tonne]	**20,161.35**
	CO2 captured from the power plant [tonnes/day]	*348.03*

Table 5. Input data and economic comparison of ‘as is’ and ‘to be’ scenarios

5. Conclusion

Researchers and companies are leaning towards CCS technologies as a relevant method of reducing CO2 emissions from large industrial sources. However, the debate about these technologies is still open even though the technologies (especially for the carbon capture process) are mature. Another interesting solution for emission reduction is carbon reuse: instead of storing the CO2, the captured CO2 could be reused in other industrial processes, thus increasing resource efficiency. Furthermore, if the CO2 reuse is developed locally (i.e. near to where it is produced), the economic (and environmental) benefits due to its utilisation could increase, allowing the support of more environmentally sustainable strategies, such as industrial symbiosis. The proposed feasibility study has outlined several results. First of all, a general guideline for supporting researchers and practitioners in developing analogous studies was proposed. Economic results obtained for the specific case have highlighted interesting potentialities of carbon capture and reuse in industrial districts. In detail, the introduction of a carbon reuse process will provide a reduction of about 42% of the annual operation costs of the sugar factory, leading to a slight reduction in yield in the power plant process. Positive impacts for the power plant are mainly focused on the environmental point of view as a reduction (about 7%) of the CO2 emission could be achieved. Further development could be oriented toward evaluating the potential benefits of carbon capture and reuse in industrial districts from an environmental point of view. These studies will support the development of new business models in managing these technologies: the power plant firm could evaluate becoming a CO2 ‘service provider’ for other firms located in the industrial districts, thus optimising its investment in carbon capture technologies. Carbon reuse processes could also be managed by an external service provider firm (public or private) aiming to both generate profit by providing CO2 to customers (e.g. firms in the industrial districts which use CO2 in their production cycles) and providing a CO2 capture service to other customers. Finally, the study has pointed out the importance of carbon reuse to support low-carbon circular economy strategies.

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